Combined effect of technical, meteorological and agronomical factors on solid-set sprinkler irrigation: I. Irrigation performance and soil water recharge in alfalfa and maize.

by

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Abstract

In this work, maize (Zea mays L.) and alfalfa (Medicago sativa L.) were irrigated in two adjoining plots with the same sprinkler solid-set system. Irrigation was evaluated between four sprinklers in the central position within each plot, above the canopy with pluviometers and in the soil with a FDR probe. Maize and alfalfa were simultaneously irrigated under the same operational and technical conditions during two seasons: in 2005, the solid-set irrigation system layout was rectangular, 15 m between sprinklers along the irrigation line and 15 m among lines (R15x15), and the seasonal irrigation applied according to the crop evapotranspiration (ET_c); in 2006, the solid-set layout was R18x15 and the seasonal irrigation was around 30 % lower than the ET_c. The irrigation depth above the canopies (ID_C) and the soil water recharge after irrigation (*RW*) were monitored using a 3x3 m^2 grid (25 points in 2005 and in 30 points in 2006). For maize, *RW* was assessed both in the lines of plants (*CL*) and between the lines (*BCL*).

The average values of ID_C were similar between crops during both seasons but the uniformity (*CUC*) of the ID_C noticeably depended on the crop: the differences were greater between crops than between sprinklers spacings (R15x15 and R18x15). The *CUC* of ID_C, the *RW* and the *CUC* of *RW* were greater for alfalfa than for maize. The *CUC* of ID_C was greater than the *CUC* of *RW* for both crops. The *RW* was significantly related with the ID_C throughout the irrigation season for alfalfa. The correlation was weaker for maize, with important differences between positions and between growth stages. At the beginning of the season, the *RW* significantly correlated with the ID_C, both in the

CL and *BCL* positions. However, the correlation weakened when the maize grew, especially in the *CL*, because the maize plants redistributed the water.

The results show that the height and canopy architecture of the crop must be considered in the analysis of the sprinkler water distribution as factors influencing the irrigation performance.

Keywords

Maize; alfalfa; uniformity; water loss; soil water; pluviometer; FDR.

1. Introduction

There have been many studies on the impact of irrigation nonuniformity on crop yield. Some of these studies have reported a low impact (Allaire-Leung et al., 2001; Li and Rao, 2003; Mateos, 1997), but others have found the crop yield to be notably influenced by the lack of irrigation uniformity (Dechmi et al., 2003a; Stern and Bresler, 1983). The conclusions of these studies highly depend on the amount of irrigation water applied and the crop surveyed. While for crops with tolerance to water stress such as cotton, carrot and wheat, the yield is not clearly affected by the irrigation uniformity, for crops with a low tolerance such as corn, irrigation uniformity and yield are strongly related.

Numerous studies (Dechmi et al., 2003b, Fukui et al., 1980; Kincaid et al., 1996; Kohl, 1974; Lorenzini, 2002; Lorenzini and De Wrachien, 2005; Playán et al., 2005; Tarjuelo et al., 1999a, 1999b; Zapata et al., 2007) have surveyed the factors influencing sprinkler irrigation performance (sprinkler type, sprinklers spacing, riser height, nozzles design, operating pressure, time of irrigation, temperature and relative humidity of the air, wind velocity and direction, etc.). Most studies put effort into technical and environmental factors, while agronomic factors have attracted less attention.

Some studies have put great stress on the redistribution of the irrigation water once the drops are intercepted by the leaves and drip through the canopy. Letey (1985) reported that the soil water uniformity is the same as the application uniformity for pressurized irrigation systems such as sprinklers when they are properly designed to avoid surface ponding. However, the uniformity of the soil water has been found to be greater than the application uniformity (Dechmi et al., 2003a; Li, 1998; Li and Kawano, 1996; Li and Rao, 2000). The horizontal redistribution of the soil water following infiltration has been reported as the main cause (Li and Kawano, 1996), but, prior to being infiltrated, the sprinkler irrigation water is partitioned by the crop canopy in three components: stemflow, throughfall and interception storage (Lamm and Manges, 2000). Consequently, the crop canopy redistributes the irrigation water (DeBoer et al., 2001; Paltineanu and Starr, 2000; Steiner et al., 1983). The microtopography of the soil surface is also relevant in the soil water distribution. When the crops grow in rows, the distribution of the roots in the soil is not uniform: the root density is higher in the crop line than between the crop lines (Anderson, 1987; Liedgens and Richner, 2001).

This study analyzes the influence of the crops on the distribution of the sprinkler irrigated water, both above the canopy and in the soil. For this study, maize and alfalfa were simultaneously irrigated under the same operational and technical conditions. This setup provides a suitable scenario for the comparison. Maize is a tall crop, arranged in rows and very sensitive to water stress, while alfalfa is a broadcast crop that is medium in height and tolerant to water stress.

2. Materials and Methods

2.1. Experimental site

The experiment was conducted at the experimental farm of the Agricultural and Food Research and Technology Centre in Zaragoza, Spain (41º43’ N, 0º48’ W, 225 m altitude). Maize and alfalfa were farmed in adjoining plots during the 2005 and 2006 seasons; in this paper they will be called alfalfa-05, alfalfa-06, maize-05 and maize-06 (Figure 1).

The climate is classified as Mediterranean semi-arid, with mean annual maximum and minimum daily air temperatures of 20.6ºC and 8.5ºC, respectively. The yearly average values for precipitation and reference evapotranspiration (ET_0) are, respectively, 330 mm and 1,110 mm. The soil is a *Typic Xerofluvent coarse loam, mixed (calcareous), mesic* (Soil Survey Division Staff, 1993).

The wind velocity (*WV*) and direction at 2 m a.g.l., temperature (*T*) and relative humidity (*RH*) of the air, sun radiation and precipitation were recorded every 30 min during both seasons by a weather station located within an adjoining grassland plot (Figure 1). In addition, *WV* at 2 m a.g.l. was recorded every 5 min by means of a 3-cup rotors anemometer Series A-100 (Vector Instruments, Rhyl, UK) connected to a data logger model CR10X (Campbell Scientific, Logan, Utah, USA).

2.2. Irrigation layout

The different crops were sprinkler-irrigated by the same solid set system, arranged in a rectangular layout: there were 15 m between the sprinklers along the irrigation line and 15 m between the lines (R15x15) in 2005 (Figures 1a and 1c) and 18 m between the sprinklers along the line and 15 m between the lines

(R18x15) in 2006 (Figures 1b and 1d). The experimental area was located between four sprinklers in the central position. The experimental areas, 225 m^2 in 2005 and 270 m^2 in 2006, were divided into square 3x3 m^2 parcels; there were 25 parcels in 2005 and 30 in 2006 (Figures 1c and 1d). These parcels were small enough to be considered uniformly irrigated.

Impact sprinklers and nozzles of the model ‘VYR 70’ (Vyrsa, Burgos, Spain) – the company is named for descriptive purposes – were installed at 2.3 m a.g.l. The study design was consistent with a real-life situation, given that this nozzle elevation is ordinarily used in the region to irrigate several extensive crops such as corn, alfalfa and cereals, depending on the market and agro-economic policies. The main nozzle included a jet-straightening vane and was 4 mm in diameter. The auxiliary nozzle was 2.4 mm in diameter.

The operating pressure was monitored at the sprinkler nozzle every 5 min by pressure transducers of the model Gems 2200B (Gems Sensors Inc., Basingstoke, Hampshire, England) connected to a data logger of the model Dickson ES120A (DicksonWare™ Addison, Illinois, USA) (Figures 1c and 1d). Field observations gave evidence of imperceptible variations in the pressure between the four evaluated sprinklers. The pressure monitored in the experimental areas may not have represented the entire system because of hydraulic variations. However, the study is not intended to evaluate the whole process of irrigation but to achieve a suitable scenario for comparing the irrigation performance for two different crops.

2.3. Soil properties

It had previously been tested if the experimental plots differed in the soil water content and in the following soil properties: field capacity (*FC*, %), wilting point (*WP*, %), water holding capacity (*WHC*, %) and bulk density (g cm^{-3}). For all the analyses in this study, the level of significance is 5 %.

The gravimetric soil water content and its variability was analyzed using soil samples collected at the beginning of the experiment at 14 sites in alfalfa-05 and at 26 in maize-05. They were collected in 30 cm layers down to a depth of 90 cm. The samples were weighed and then oven-dried to a constant weight at 105°C. For the samples collected in the upper 30 cm layer, *FC*, *WP* and *WHC* were estimated at the laboratory using pressure plates. Values of 0.03 and 1.5 MPa were considered representative of *FC* and *WP*, respectively. *WHC* was calculated as the difference in the soil water content between *FC* and *WP*.

The soil bulk density was assessed from undisturbed samples collected in 10 cm layers down to a depth of 80 cm (73 samples from maize-05 and 61 from alfalfa-05). The variation in bulk density between experimental plots and soil depths was analyzed through an analysis of variance. The means were compared using the *lsmeans* method and the *Bonferroni's adjust* (Devore and Peck, 1986).

2.4. Agronomic facts

Maize (Zea mays L.) was sown on April 20, 2005 and April 28, 2006, 83,000 plants ha^{-1} in density, with rows 0.75 m apart. The cultivar was Pioneer PR34N43, a medium season length (FAO 500) commercial brand hybrid. Alfalfa (Medicago sativa L.) *cv.* Aragón was sown on March 17, 2005 with a sowing rate of 35 kg ha^{-1}. Plowing, fertilization, weeding, pest and disease control followed the standard practices in the area.

Crop water requirements (ET_c) were computed according to the FAO Penman-Monteith method (Allen et al., 1998) using the measurements from the weather station and the crop coefficients from Martínez-Cob (2008) for maize and from the local Irrigation Advice Service (Oficina del regante, 2006) for alfalfa.

For the 2005 season, full irrigation was planned, but some irrigation water deficit was induced for the 2006 season to analyze the relationship of the crop growth and yield with the uniformity-efficiency of the irrigation under different conditions.

2.5. Measurements of the irrigation performance parameters

The irrigation depth above the canopy (ID_C, mm) was collected in pluviometers just after each irrigation event. The pluviometers were fixed in the centre of each 3x3 m^2 parcel. Their mouths were located at 0.5 m a.g.l. at the beginning of each season (Figures 1c and 1d) and elevated as crops grew to be always above the canopy. The maximum elevation of the pluviometers was 0.9 m a.g.l. for alfalfa and 2.5 m for maize in 2005; they were 0.9 m and 2.25 m, respectively, in 2006 (Figure 1 in the companion paper regarding the 2006 season). The pluviometers were conical in the lower part and cylindrical in the upper part: 175 mm in height with a diameter of 79 mm in the upper part for the 2005 season; 373 mm and 159.6 mm, respectively, for the 2006 season. This pluviometer was specifically designed (Playán et al., 2005) to minimize experimental errors in sprinkler irrigation evaluations. For the remainder of the manuscript, variables including the subscript *i*, such as ID_{Ci}, refer to each monitoring position. In contrast, variables without the subscript *i*, such as ID_C, refer to values averaged within the experimental area. Differences in ID_C between the crops were analyzed using a *paired t-test* (Bowley, 2004).

The soil water recharge after irrigation (RW_i) was calculated as the difference between the soil water content (SWC_i, mm) before irrigation and 24 h after as in Starr and Timlin (2004). RW_i was also calculated 6 h after irrigation for alfalfa-06. For maize-05, RW_i was calculated at positions along the crop lines (*CL*) and between the crop lines (*BCL*): these were named RW_{CL} and RW_{BCL}. In 2006, *RW* was not evaluated for maize. SWC_i was estimated using a capacitance frequency domain reflectometer probe, model Diviner 2000 (Sentek Pty Ltd., Kent town, South Australia). Access tubes, 1 m in depth, were vertically inserted into the soil in early May, 2005. Twenty-five access tubes, one per parcel, were inserted in alfalfa-05 and fifty (one at *CL* and one at *BCL* per parcel) in maize-05 (Figure 1c). Five additional tubes were installed in alfalfa-06 because of the increase in the spacing between sprinklers in 2006 (Figure 1d). SWC_i was monitored every 10 cm, down to 80 cm in depth. The access tubes were installed according to the slurry installation method because gravels were present in the soil: a slightly oversized hole was drilled and partly filled with a mud mixture to fill the spaces where air would normally gather (Sentek, 2000).

A custom calibration based on the specific soil characteristics and conditions of the experiment is always highly recommended using capacitance probes. However, here the manufacturer calibration was used because the study was focused on the spatial and temporal variation of *RW* and not in the absolute values of *SWC*.

The Christiansen Uniformity Coefficient (*CUC*, %) (Christiansen, 1942) and the wind drift and evaporation losses (*WDEL*, %) were assessed for the analysis. *WDEL* above the canopy was estimated as the percentage of water emitted by the sprinklers (ID_D, mm) but not collected inside the pluviometers (ID_C) (Dechmi et al., 2003a; Playán et al., 2005):

$$WDEL = \frac{ID_D - ID_C}{ID_D} \times 100 \quad (1)$$

$$ID_D = \frac{Q \times t}{l \times s} \quad (2)$$

where Q (l s^{-1}) is the sprinkler flow rate, t (s) the operating time, l (m) the spacing between laterals and s (m) the spacing between sprinklers along the lateral (m). Q was calculated according to Torricelli's Theorem and the Orifice Equation (Norman et al., 1990):

$$Q = 0.00035 \times \pi \times C_D \times A \times \sqrt{2gp} \quad (3)$$

where C_D is the discharge coefficient (value = 0.98), A (mm^2) the area of the nozzles orifices, g (m s^{-2}) the gravity acceleration and p (kPa) the pressure at the nozzle. Playán et al. (2006) calibrated the orifice flow equation of the *VYR 70* sprinkler model for various operating pressures by measuring the flow rate in the field.

2.6. Crop growth and yield

Six plants of maize per parcel (three plants per line, arranged in the two central lines) were labeled, and their height was measured weekly.

For three crop lines within each parcel, the plants in one meter were hand-harvested (25 % of the experimental area) on September 27 for maize-05 and on September 26 for maize-06. The weight of the maize kernels, adjusted to a moisture content of 14 %, was the grain yield (*GY*, kg ha^{-1}). The vegetative dry matter production (*VDM*, kg ha^{-1}) was determined. The *VDM* plus the weight of the ears equaled the total aerial plant dry matter (*DM*, kg ha^{-1}).

Alfalfa was mown when the crop was in the ½ bloom growth stage as the highest hay productions are obtained at this phenological phase (Orloff and Carlson, 1998). Because the alfalfa crop had just been established, the first cutting, on May 19, 2005, was not controlled. The above ground parts of alfalfa were mown in square samples of 0.25 m^2 (enlarged to 0.5 m^2 in 2006), one per parcel. The cutting dates were June 21, July 25 and August 26 in 2005 and June 15, July 10, August 3 and September 6 in 2006. The samples were weighed and then dried to a constant weight at 60ºC, and the hay dry matter (*HY*, kg ha^{-1}) was assessed.

3. Results and Discussions

3.1. Soil characteristics related to water

The soil bulk density did not differ among plots or among parcels within each plot. However, the soil depth had a significant effect (Table 1). The soil bulk density was lowest in the 20 cm upper layer (1.47 g cm^{-3} in average) and increased in the lower layers (1.59 g cm^{-3} from 40 to 60 cm). Compression of the lower layers by the tillage and the development of the root system in the upper layers have been found to be an explanation for this phenomenon (Ahuja et al., 1998; DeBoer et al., 2001; Starr et al., 1995; Timlin et al., 2001).

The *FC* did not differ between plots and was, on average, 26.6 % in volumetric percentage and 79.8 mm for the upper 30 cm layer (Table 2). The *WP* was significantly different between plots, but this difference was lower than the standard deviation of the samples. The *WHC* was also found to be significantly different: within the 0-30 cm profile, the *WHC* was 6.0 mm greater for maize-05 (49.2 mm) than for alfalfa-05 (43.2 mm). The slight difference in the *WHC* between plots was not relevant in terms of water availability for the crops because frequent irrigations were scheduled in this experiment.

The *SWC* at the beginning of the experiment was similar for alfalfa-05 and maize-05 within the 0-60 cm soil profile: when calculated in 30 cm layers, the *SWC* ranged from 63 to 68 mm. However, within the 60-90 cm layer, the *SWC* was higher in maize-05 (81.9 mm) than in alfalfa-05 (66.3 mm). Assuming the same *FC* level as that assessed for the 0-30 cm layer, the deeper layer at maize-05 was saturated when the experiment began. In the maize-05 plot, irrigation water was applied in excess during a previous trial throughout 2003 and 2004. In contrast, the alfalfa-05 plot was fallow land during that time. This difference explains the water accumulation at the bottom layers in maize-05. Because frequent irrigation was scheduled, the variations in *SWC* were expected to occur in the upper layers. Therefore, the differences in *SWC* within the bottom 60-90 cm layer at the beginning of the experiment were not considered to be a constraint for the comparison between crops.

The *SWC* variability at the beginning of the experiment increased with depth and was greater in alfalfa-05 than in maize-05: the coefficient of variation (*CV*) of *SWC* was 8.6 % (0-30 cm profile), 10.6 % (30-60 cm) and 17.1 % (60-90 cm) for alfalfa-05; it was 6.3 %, 8.2 % and 11.5 % for maize-05. Several studies have reported that the variability in *SWC* increases as *SWC* decreases (Miyamoto et al., 2003; Nielsen and Bigger, 1973; Rajkai and Ryden, 1992). However, in our experiment, the variability in *SWC* increased in the lower layers because of the proliferation of stones.

3.2. Irrigation performance above maize and alfalfa.

For maize-05, the seasonal ET_c was 842 mm (from sowing on April 20 to harvest on September 27) while the seasonal ID_C was 546 mm and the rainfall was 145 mm. For alfalfa-05, the seasonal ET_c was 580 mm (from the first cutting on May 19 to the last cutting on August 26) while the seasonal ID_C was 537 mm and the rainfall was 64 mm. The seasonal ET_c, ID_C and rainfall were, respectively, 812, 420 and 177 mm for maize-06 (from April 28 to September 26) and 633, 396 and 61 mm for alfalfa-06 (from May 16 to September 6).

Until the last irrigation event (August 23), maize-05 received 93 % of the accumulated ET_c (82 % accounting for the complete crop season) while alfalfa-05 received 103 %. Thus, the irrigation scheduling nearly matched the water needs of the crops in 2005, although irrigation was prematurely finished for maize-05. In 2006, maize and alfalfa received 73 and 72 %, respectively, of their water needs during the irrigation season.

The environmental conditions were alike for both seasons (Table 3). The ID_C was not different above maize or alfalfa (paired t-test; Bowley, 2004; Figure 2).

The difference in ID_C between seasons is related to the decrease in ID_D. According to Eqs. 2 and 3, ID_D increases with p and t and decreases with l and s. Small differences were monitored in p and t between crops and among irrigation events. The increase in the spacing between sprinklers from R15x15 (2005) to R18x15 (2006) resulted in the average pluviometry of the irrigation system decreasing from 7.0 mm h^{-1} to 5.8 mm h^{-1} (considering an operating pressure of 350 kPa).

The differences in ID_C among irrigation events, as illustrated in the scattering along the 1:1 line of Figure 2, were mainly due to the variations in *WDEL* (Eq. 1) among dates. *WV* is the main meteorological variable affecting *WDEL* (Dechmi et al., 2003a; Kincaid et al., 1996; Playán et al., 2005; Seginer et al., 1991a, 1991b; Tarjuelo et al., 1994), and the variability of *WV* among irrigation events was important (Table 3).

3.2.1. Sprinkler irrigation uniformity above maize and alfalfa canopies

The *CUC* of the ID_C clearly differed depending on the crop irrigated and was about 8 units (%) greater above alfalfa than above maize (Table 3). The differences increased as the uniformity decreased, and they depended on the solid set arrangement (Figure 3). The irrigated crop had an even greater impact on the sprinkler irrigation uniformity than did the solid set layout. Our companion paper investigates the effects of the crops on the *CUC* through their influence on the water collecting level and on the wind conditions above the canopy.

The regression lines shown in Figure 3 were found to be parallel according to the analysis proposed by Larsen (2006). According to a parallelism constraint, the relationship between the *CUC* evaluated above alfalfa (CUC_a) and the *CUC* evaluated above maize (CUC_m) was:

$$CUC_a = 0.48 \times CUC_m + 51.3 \ (R^2 = 0.82); \text{ for the R15x15 layout.} \quad (4)$$

$$CUC_a = 0.48 \times CUC_m + 47.7 \ (R^2 = 0.78); \text{ for the R18x15 layout.} \quad (5)$$

Eqs. 4 and 5 indicate that the irrigation uniformity noticeably differed with the crop, being greater above alfalfa. The solid set sprinkler spacing increased the differences between crops.

As reported Dechmi et al. (2003b), the seasonal uniformity coefficient (CUC_S), calculated from the ID_{Ci} accumulated throughout the season, was greater than the seasonal average *CUC* (Table 3). This trend became more noticeable by increasing the spacing of the sprinklers. The difference in the CUC_S was also greater between crops than between solid-set arrangements.

The average *CUC* of the ID_C was calculated for each alfalfa growing period, from the first to the last controlled cutting, and was 94, 89 and 90 % in 2005, and 79, 84, 88 and 84 % in 2006 (CUC_S resulted very similar to the average *CUC* of ID_C).

3.2.2. Wind drift and evaporation losses above maize and alfalfa canopies

WDEL noticeably increased with the sprinkler spacing (greater for R18x15 in 2006) (Table 3, Figure 4). According to a paired t-test, *WDEL* was significantly different between crops in 2006 (R18x15) but not in 2005 (R15x15). The *WDEL* assessed above maize were greater than those above alfalfa for 50 % of the irrigation events in the case of the R15x15 layout, but for 75 % of the events for the R18x15 layout. The intercepts of the regression lines were not significant, and the dispersion was greater for the R15x15 layout.

The differences in the pluviometer sizes, which were smaller in 2005 (R15x15), could have introduced noise into the comparison between seasons, both on the dispersion and on the values of *WDEL* (Playán et al., 2005). The differences between crops in *p*, although small (larger during 2006), can explain part of the results because droplet size decreases with *p*, and small droplets are more susceptible to evaporation and wind-drift (Playán et al., 2005). In addition, sprinkling affects the microclimate of an irrigated area, decreasing the vapor pressure deficit and air temperature (Cavero et al., 2009; Playán et al., 2005; Robinson, 1970; Tolk et al., 1995). The vapor pressure deficit and air temperature may have increased in 2006 (R18x15) with respect to 2005 (R15x15) because of the decrease in the pluviometry of the irrigation system. However, these considerations must be considered carefully as microclimate changes were not measured above the canopy.

The analysis in the companion paper revealed that the distance between nozzles and pluviometers affected the evaluation of ID_C, and thus the estimate of *WDEL*. The dispersion in the comparison shown in Figure 4 is also related to this fact as the collecting level was disregarded. A thorough analysis of the differences in *WDEL* between crops, considering the elevation of the pluviometers and the *WV* above each crop, is included in the companion paper.

3.2.3. Soil water recharge for maize and alfalfa.

The *RW* was found to differ depending on the crop and on the measurement position for maize (Figure 5), although the ID_C was similar for both crops (Figure 2).

In 2005, calculated 24 h after irrigation and within the 0-80 cm soil profile, the RW_{CL} was 9.0 ± 3.0 mm (average ± standard deviation) and the RW_{BCL} was 5.6 ± 2.8 mm. These values accounted for 48 % and 30 % of the ID_C, respectively. The ratio of *RW* within the 0-30 cm soil profile to *RW* within the 0-80 cm soil profile was 83 % in *CL* and 81 % in *BCL*. Starr and Timlin (2004) found similar results. An RW_{CL} greater than the RW_{BCL} stems from the greater macroporosity in *CL*, the funneling effect of the maize plants (Paltineanu and

Starr, 2000) and the larger density of roots in *CL* (Anderson, 1987; Liedgens and Richner, 2001).

Within the 0-80 cm soil profile, the *RW* 24 h after irrigation was 10.4 ± 4.0 mm for alfalfa-05 (54 % of ID_C), 96 % of which were retained within the 0-30 cm soil profile. For alfalfa-06, the *RW* was 9.0 ± 4.0 mm (61 % of ID_C), 98 % of which were retained within the 0-30 cm profile. Calculated from thirteen events, the *RW* was 14.1 ± 3.1 mm 6 h after irrigation (93 % of ID_C). Similar results have been reported previously (Hupet and Vanclooster, 2005).

According to a parallelism constraint (Larsen, 2006), the relationship between RW_m and RW_a (Figure 5) was (in mm):

$$RW_{CL} = 0.61 \times RW_a + 2.6; \ (R^2 = 0.72) \quad (6)$$

$$RW_{BCL} = 0.61 \times RW_a - 1.0; \ (R^2 = 0.59) \quad (7)$$

According to Eqs. 6 and 7, RW_a and RW_{CL} were greater than RW_{BCL}. This outcome is related to the redistribution of the irrigation water by the maize plants. *Throughfall*, supplying water into the *BCL* positions is smaller than *stemflow*, supplying water into the *CL* positions, and noticeably smaller than ID_C. Throughfall ratios between 35 % and 84 % of the ID_C have been found (Paltineanu and Starr, 2000) and were around 20 % for rainfall (Hupet and Vanclooster, 2005). In addition, the infiltration might have been limited in *BCL* due to sealing and compaction of the soil in *BCL* before the canopy covered the soil, while the soil was protected beneath the canopy in *CL* (Ben-Hur et al., 1989).

RW_a was greater than RW_{CL} in most irrigation events (Figure 5); for values greater than 6.7 mm according to Eq. 6. The S*temflow* above *CL* is not lower than the ID_C (Hupet and Vanclooster, 2005; Paltineanu and Starr, 2000), and the average ID_C was similar above maize and alfalfa (Table 3, Figure 2). The differences between RW_a and RW_{CL} were related to the *CUC* of the ID_C, which was lower for maize (Figure 3). When the *CUC* of the ID_C is low, the average *RW* decreases because *RW* is low in the least irrigated areas, and *RW* is limited by the water holding capacity and the infiltration rate in the areas receiving more water. In addition, the *SWC* before irrigation, the soil hydraulic properties and its spatial variability, the water interception by the canopy and the soil, the soil water extraction rate by the crops and the accuracy and precision of the instruments employed, among other variables, are factors related to the *RW*.

The *CUC* of the *RW* was related to the *CUC* of the ID_C, but the former was smaller, especially for maize in *BCL* (Figure 6). In 2005, the average *CUC* of RW_{CL} was 57 ± 11 %, the *CUC* of RW_{BCL} was 50 ± 22 % (Figure 6a) and the CUC_a of *RW* was 77 ± 9 % (Figure 6b). Dechmi et al. (2003a) found the same trend for maize. Thus, CUC_a was greater than CUC_m both for ID_C and *RW*.

For alfalfa-06, the increase in the sprinkler spacing (R18x15 vs. R15x15) decreased both the *CUC* of the ID_C and the *CUC* of the *RW* (data not presented). The *CUC* of the *RW* was greater 6 h after irrigation than it was 24 h afterward (76 ± 9 % vs. 70 ± 14 %). Spatial differences in the water withdrawals by the alfalfa plants in the lapse between 6 and 24 h could be a feasible explanation for this phenomenon.

3.2.4. Correlation between water collected above the canopy and that retained in the soil: Differences between maize and alfalfa.

The correlation between ID_{Ci} and RW_i 24 h after irrigation illustrated differences between crops, and between positions for maize.

RW_{iCL} and ID_{Ci} were significantly correlated only in seven of the twenty-three events monitored in 2005, three of which were performed in June during the earliest maize growing stage. The sample linear correlation coefficient (r) ranged between 0.40 and 0.54. In *BCL*, r ranged between 0.41 and 0.71 (the greatest for the event performed on June 1), and the correlation was significant for eleven events.

For alfalfa, the r ranged between 0.40 and 0.75 in 2005. The correlation, consistent throughout the season, was significant for fifteen events. In 2006, RW_i significantly correlated with ID_{Ci} in all but one of the irrigation events, and r ranged between 0.40 and 0.80. Similar results were obtained if plants were monitored 24 or 6 h after irrigation.

The correlation between RW_i and ID_{Ci} was not clearly related with the *CUC* of the ID_C for maize. In contrast, it was with alfalfa during both seasons: r was high for values of the *CUC* of the ID_C below 85 % while the r scattered for values above 85 %.

Two issues were particularly related to the lack of correlation between ID_{Ci} and RW_{iCL}: the funneling effect of the maize plants and the preferential water uptake by the roots (Paltineanu and Starr, 2000). Both imply a redistribution of the water with respect to that collected above the canopy and depend on the stage of growth and the rate and duration of the rainfall (Quinn and Laflen, 1983; Timlin et al., 2001). Besides the differences between maize positions, these processes are also related to the differences between crops.

The differences in the correlation between ID_{Ci} and RW_i between crops and maize positions are illustrated for three irrigation events (Figure 7), one at the beginning of the season (June 1) and two others performed after maize reached its maximum height but in different physiological phases (July 7 and August 19). All events were performed under windy conditions (average *WV* equal to 3.5, 4.3 and 5.0 m s^{-1}, respectively), high temperature (25, 24 and 26 ºC) and low relative humidity (42, 37 and 47 %). For each of them, the *CUC* of the ID_C was, respectively, 88, 87 and 79 % for alfalfa and 86, 68 and 65 % for maize; the *WDEL* was 6, 12 and 13 % for alfalfa and 13, 11 and 16 % for maize.

Figure 7 summarizes the effects of the crops on the distribution of the irrigation performance and the differences between maize and alfalfa. The *CUC* of the ID_C was greater above alfalfa than above maize. The *RW* was greater for alfalfa. RW_i was related to ID_{Ci} throughout the entire season for alfalfa (*r* ranged between 0.67 and 0.70 for these three events). This correlation was weaker for maize, with visible differences among positions and growing stages. At the beginning of the season (June 1), RW_i significantly correlated with ID_{Ci} in both *CL* and *BCL* positions (*r* equal to 0.54 and 0.71, respectively). The correlation decreased as the maize grew. The water redistribution in the soil was greater in *CL*: for the events on July 7 and August 19, *r* equaled 0.48 and 0.51, respectively, in *BCL*, but the correlation was not significant in *CL*.

In areas devoted to extensive crops such as alfalfa and maize, the designs of solid-set sprinkler irrigation systems are very homogeneous (Zapata et al., 2009). Commonly, the elevation of the sprinkler nozzles in these areas is around 2 m a.g.l., irrespective of the crop. The results presented in this work stressed the influence of the crops on the sprinkler irrigation. Consequently, the crop to be irrigated must be considered when designing and managing the irrigation system.

3.3. Yield and irrigation water supply

The electrical conductivity (*EC*) of the irrigation water during the 2005 and 2006 irrigation season was around 2 dS m^{-1}. Experiments in the same field found that irrigation water with *EC* ranging from 0.4 to 4.7 dS m^{-1} did not decrease the cumulative hay production of two-year-old alfalfa and that 2.2 dS m^{-1} was a threshold above which the maize yield declined (Isla et al., 2006). Thus, yield detriments because of irrigation water salt load were not expected.

3.3.1. Maize yield

In 2006, the water supply for maize constituted 73 % of the accumulated ET_c, while this figure was 82 % in 2005. However, the ratio of the *DM* in 2006 to the *DM* in 2005 was 53 % (Table 4). With regard to the partition of biomass between the vegetative and reproductive fractions, the decrease was noticeably greater for the reproductive organs. The *VDM* and *GY* for maize-06 were, respectively, 68 % and 47 % when compared with maize-05. This percentage is smaller than others previously reported (Aguilar et al., 2007; Farré and Faci, 2006; O'Neill et al., 2004). Between seasons, the average *GY* increased with the average ID_C (Table 4, Figure 8).

Within the experimental areas, the GY_i increased with the ID_{Ci} (Figure 8). The increase diminished as maize reached its potential maximum yield (not found for this experiment). The relationship between the GY_i and ID_{Ci} varied depending on the crop season: many parcels received similar seasonal ID_{Ci} but the GY_i differed greatly depending on the season (points between dashed lines, Figure 8) because it was mainly related to the irrigation schedule and the irrigation uniformity, both of which were dissimilar for each season.

The effects of the irrigation uniformity on the *GY* were stressed in 2006 because the water supply decreased. In 2005, GY_i and the seasonal ID_{Ci} were not significantly correlated, but they were in 2006 (r equal to 0.62). The CUC_S of the ID_C in 2006 were greater than in 2005 (Table 3), but the *CUC* of the *GY* was noticeably lower (Table 4).

The maize growth was limited in 2006. The maximum height of the plants (h) was, on average for the experimental plot, 2.22 m in 2005 but 1.75 m in 2006 (Figure 1 in the companion paper for the latter). The variability of h decreased during the season and was noticeably greater in 2006: at the end of June, the *CV* was 11 % in 2005 but 21 % in 2006; at the end of July, it was 5 % in 2005 but 12 % in 2006.

These results suggest that irrigation during the earliest growing period was relevant. For the parcels between the dashed lines (Figure 8), the ID_{Ci} that accumulated during June 2005 was 148 mm, and its spatial uniformity was 82 %, but in 2006 it was 132 mm and 71 %, respectively.

Maize is highly sensitive to water stress during flowering (Andrade and Ferreiro, 1996; Cakir, 2004; Otegui and Slafer, 2000; NeSmith and Ritchie, 1992), and the quality of the irrigation performance during this critical period can be more relevant than the seasonal irrigation distribution (Dechmi et al., 2003a). For five irrigation events in 2005, the GY_i was found to be significantly correlated with the ID_{Ci} collected on June 22, July 1, 4 and 5 and August 16.

The coefficient *r* ranged between 0.4 and 0.6; these values are similar to those previously reported by others (Dechmi et al., 2003a). Three of the events were performed in July, within the flowering period, and resulted in a *CUC* of the ID_C lower than 66 %. In 2006, the GY_i was significantly correlated with the ID_{Ci} for thirteen events (*r* ranged between 0.38 and 0.59). The correlation did not depend on the development stage, but those events resulted in a *CUC* of the ID_C lower than 85 % (with the exception of three of them).

3.3.2. Alfalfa yield

It must be considered that alfalfa shows specific variations between seasons and between growing periods within the season. The seasonal *HY* was 10,579 kg ha^{-1} in 2005 when supplied with 103 % of the seasonal ET_c, and 13,201 kg ha^{-1} in 2006 when supplied with 72 % of the seasonal ET_c; these figures are below the 15,000 kg ha^{-1} value reported as the average in the Ebro Valley (Spain) (Dechmi et al., 2003b). In 2005, as it was the establishing season, the alfalfa was mowed only three times. In contrast, four cuttings were performed in 2006. This difference explains the lower seasonal *HY* in 2005. When averaged per cutting, the *HY* was greater in 2005 than in 2006 (Table 4), in concordance with the water supply. The interval between cuttings in 2005 ranged between 32 and 34 days. Alfalfa weakens after the first growing season if this interval is less than 30 days (Orloff and Carlson, 1998). In 2006, the interval ranged between 24 and 34 days.

From the first to the last cutting, the average *HY* was 2,732, 4,210 and 3,637 kg ha^{-1} in 2005 and 4,195, 3,736, 2,995 and 2,275 kg ha^{-1} in 2006. In agreement with previous studies (Orloff and Carlson, 1998; Smeal et al., 1991), the *HY* decreased from the first to the last cutting (except in the case of the first cutting in 2005). In 2005, the *HY* was limited for the first cutting because the alfalfa plants were not fully mature at the beginning of the establishing season, and the root reserves that were kept as carbohydrates were not sufficiently stored.

The HY_i and the ID_{Ci} were averaged per cutting to allow a comparison in spite of intra and inter-annual variation. On average, no important differences were found between the seasons (the *HY* per cutting in 2006 was 94 % of that in 2005, Table 4) despite the differences in the water supply. The cumulative ID_C during the growing period was 179 mm cutting^{-1} in 2005 but 99 mm in 2006. Because the average ET_c in 2006 was 158 mm cutting^{-1}, it can be inferred that the water previously stored in the soil was an important source for alfalfa-06. The *CUC* of *HY* was high for both seasons (Table 4), greater than 85 % for every cutting, which was related to the high values of the *CUC* of the ID_C (Table 3).

The HY_i was not significantly correlated with the ID_{Ci} in 2005. In 2006, when the water supply decreased, the HY_i and the ID_{Ci} were significantly correlated for the five irrigation events performed during the second and fourth growing periods, all of which resulted in a *CUC* of the ID_C lower than 80 %. For these correlations, the *r* ranged between 0.45 and 0.64. Orloff and Carlson (1998) reported that transpiration alone explains 61 % of the *HY*.

4. Conclusions

The average irrigation depth above the canopy (ID_C) was very similar for maize and alfalfa simultaneously irrigated with a solid-set sprinkler system. In contrast, the average Christiansen's Uniformity Coefficient (*CUC*) of the ID_C was

8 units (%) greater above the alfalfa. The average *CUC* of the ID_C was 5 units (%) greater for the R15x15 solid-set layout than for the R18x15 layout. In consequence, the crop irrigated had a greater impact on the water spatial distribution than the sprinklers spacing.

The wind drift and evaporation losses (*WDEL*) resulted slightly greater above the maize: the average *WDEL* assessed for the R15x15 solid-set was 11 % above the maize and 10 % above the alfalfa; 18 % and 16 %, respectively, for the R18x15 solid-set. The differences in the *WDEL* were significantly different between the crops only for the R18x15 layout.

Differences were also found between the crops, and between the positions for maize in the soil water recharge after irrigation (*RW*). The alfalfa retained more water than the maize. The differences were related to the irrigation uniformity above the canopy, greater above the alfalfa. The *RW* was greater in the crop lines (*CL*) than between the crop lines (*BCL*) for maize. Several phenomena are related to these results: in the *CL*, the incident rainfall (*stemflow*) is greater than the incident water in *BCL* (*throughfall*) because the funneling effect by the maize plants; in addition, the soil may crust in *BCL* because of the impact of the water drops, while the canopy protects the soil beneath in *CL*.

The *CUC* of *RW* was smaller than the *CUC* of ID_C for both crops. The *RW* significantly correlated with the ID_C throughout the irrigation season for alfalfa. For maize, the correlation was weaker, with important differences between the positions and between the growth stages. At the beginning of the season, the *RW* and the ID_C significantly correlated in the *CL* and *BCL* positions, but the correlation decreased, especially in the *CL* position, when the maize developed because the redistribution of the irrigation water in the soil.

The influence of the irrigation performance on the crops growth and yield depends on the irrigation dose, uniformity and schedule. The influence of the *CUC* of the ID_C for maize increases under water stress and it is particularly significant during the earliest growth period and during the flowering stage. For alfalfa, the influence of the *CUC* of the ID_C on the yield is limited when the crop is not severely stressed. In addition to the tolerance of the alfalfa to the water stress, this is related to the irrigation uniformity above the canopy and in the water recharge, both greater for the alfalfa than for the maize.

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7. Nomenclature

A = *Area of the nozzles orifices* (mm^2)

a.g.l. = *Above the ground level*

BCL = *Between-crop-lines position in maize*

C_D = *Discharge coefficient (value = 0.98)*

CL = *Crop-lines position in maize*

CUC = *Christiansen's Uniformity Coefficient (%)*

CUCa = *CUC above alfalfa (%)*

CUCm = *CUC above maize (%)*

CUC_S = *Seasonal Christiansen's Uniformity Coefficient (%)*

CV = *Coefficient of variation*

DM = *Total aerial plant dry matter* ($kg\ ha^{-1}$)

EC = *Electrical conductivity* ($dS\ m^{-1}$)

ET_0 = *Reference evapotranspiration (mm)*

ET_c = *Crop evapotranspiration (mm)*

FC = *Field capacity (%)*

g = *Gravity acceleration* ($m\ s^{-2}$)

GY = *Grain yield averaged for the experimental area* ($kg\ ha^{-1}$)

GY_i = *Grain yield for a parcel* ($kg\ ha^{-1}$)

HY = *Hay dry matter averaged for the experimental area* ($kg\ ha^{-1}$)

HY_i = *Hay dry matter for a parcel* ($kg\ ha^{-1}$)

ID_C = *Average irrigation depth collected in the experimental area (mm)*

ID_{Ci} = *Irrigation depth collected into a pluviometer (mm)*

ID_D = *Irrigation depth emitted by the sprinklers (mm)*

l = *Spacing among laterals (m)*

p = *Pressure in nozzle (kPa)*

Q = *Sprinkler flow rate (l s^{-1})*

r = *Sample linear correlation coefficient*

R^2 = *Coefficient of determination*

RH = *Air relative humidity (%)*

RW = *Soil water recharge averaged for the experimental area (mm)*

RW_a = *Soil water recharge in alfalfa (mm)*

RW_{BCL} = *Soil water recharge in BCL (mm)*

RW_{CL} = *Soil water recharge in CL (mm)*

RW_i = *Soil water recharge estimated for a parcel (mm)*

s = *Spacing among sprinklers along the lateral (m)*

SWC = *Soil water content averaged for the experimental area (mm)*

SWC_a = *Soil water content averaged in alfalfa (mm)*

SWC_{BCL} = *Soil water content in the between-crop-lines position (mm)*

SWC_{CL} = *Soil water content in the crop-lines position (mm)*

SWC_i = *Soil water content measured in a parcel (mm)*

T = *Air temperature (ºC)*

t = *Operating time of the irrigation event (s)*

VDM = *Vegetative dry matter production (kg ha^{-1})*

WDEL = *Wind drift and evaporation losses (%)*

WHC = *Water holding capacity (%)*

WP = *Wilting point (%)*

WV = *Wind velocity (m s^{-1})*

List of Tables

Table 1: Average soil bulk density.

Depth (cm)	10	20	30	40	50	60	70
Mean (g cm^{-3})	1.48 a	1.46 a	1.55 ab	1.61 b	1.60 b	1.57 b	1.53 ab

Values followed with the same letter are not significantly different (α = 0.05).

Table 2. Soil water properties: Average values ± standard deviation of the Wilting Point (WP), Field Capacity (FC) and Water Holding Capacity (WHC) for the surface layer (0-30 cm) expressed as a volumetric percentage.

	Alfalfa-05	Maize-05	All
Number of samples	14	26	40
WP (%)	11.5 ± 1.05	10.5 ± 1.09	10.9 ± 1.17
FC (%)	25.9 ± 2.11	26.9 ± 1.97	26.6 ± 2.05
WHC (%)	14.4 ± 1.73	16.4 ± 1.50	15.7 ± 1.83

Table 3. Summary of the characteristics of the irrigation seasons 2005 and 2006: Solid-set arrangement [Rectangular (R) distance among sprinklers x distance among laterals (m)], number of irrigation events, dates of first and last irrigations, wind velocity (WV), temperature (T) and relative humidity (RH) of the air during the irrigation events, irrigation time (t), operating pressure at the nozzle (p), irrigation depth applied (ID_D), irrigation depth collected above the canopy (ID_C), Christiansen's Uniformity Coefficient (CUC) of ID_C, seasonal CUC of ID_C (CUC_s) and wind drift and evaporation losses (WDEL).

	2005		2006	
	Maize	Alfalfa	Maize	Alfalfa
Solid set arrangement	R15x15		R18x15	
Irrig. events	29	28	29	27
Irrigation season	06/01 – 08/23	06/1 – 08/23	05/31 – 09/19	05/31 – 09/04
WV (m s^{-1})	2.8 ± 1.5[a]		2.8 ± 1.8[a]	
T (ºC)	28 ± 3[a]		27 ± 4[a]	
RH (%)	42 ± 9[a]		42 ± 12[a]	
t (h ± min)	3 ± 9[a]		3 ± 7[a]	
p (kPa)	349 ± 15[a]	346 ± 11[a]	363 ± 46[a]	346 ± 34[a]
ID_D (mm)	20.9 ± 1.2[a]	20.5 ± 1.0[a]	17.7 ± 1.6[a]	17.3 ± 1.4[a]
ID_C (mm)	18.8 ± 1.5[a]	19.2 ± 2.0[a]	14.5 ± 1.4[a]	14.7 ± 1.8[a]
CUC ID_C (%)	81 ± 10[a]	90 ± 5[a]	76 ± 13[a]	84 ± 7[a]
CUC_S ID_C (%)	87	96	89	94
WDEL (%)	11 ± 5[a]	10 ± 6[a]	18 ± 9[a]	16 ± 11[a]

[a] Seasonal average value ± standard deviation.

Table 4. Summary of the yield for the 2005 and 2006 seasons: Seasonal average of the total aerial plant dry matter (DM, kg ha^{-1}), vegetative dry matter (VDM, kg ha^{-1}) and grain yield (GY, kg ha^{-1}) for the maize, hay yield (HY, kg ha^{-1} cutting^{-1}) per cutting for the alfalfa and Christiansen's Uniformity Coefficient (CUC, %) of these parameters.

		Maize			Alfalfa
		DM	VDM	GY	HY
2005	Average	25,993	9,046	13,630	3,526
	CUC	93	90	93	93
2006	Average	13,712	6,134	6,353	3,300
	CUC	80	84	68	94

List of Figures

Figure 1. Experimental design. Aerial view of the experimental plots in the 2005 (a) and 2006 (b) seasons. The experimental areas between four sprinklers are shaded in grey. Instrumental settings in the 2005 (c) and 2006 (d) seasons.

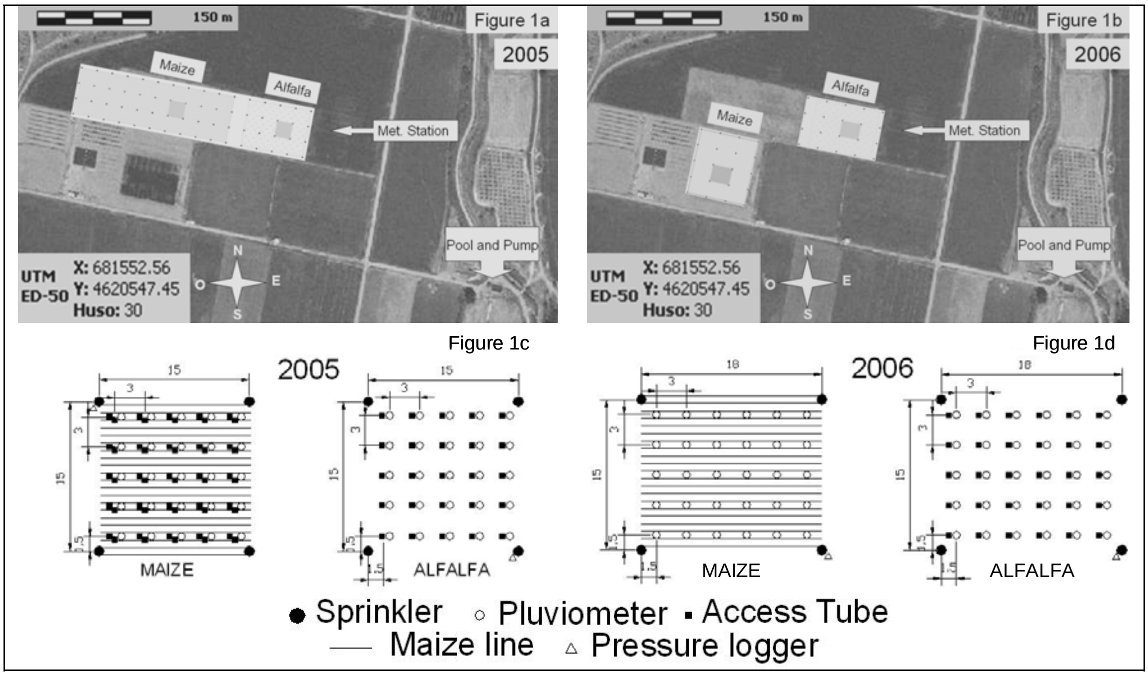
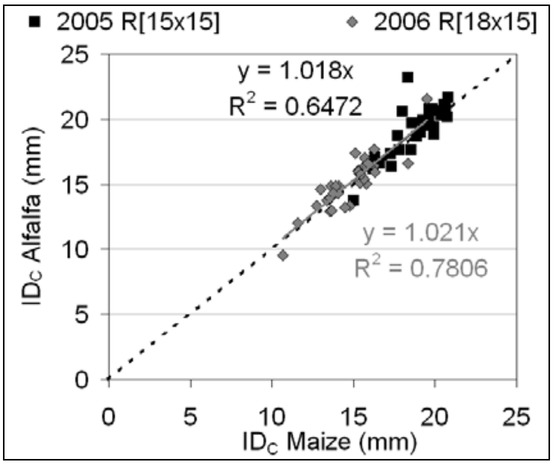


Figure 2. Comparison of the average irrigation depth (ID_C) collected into the pluviometers above maize and alfalfa for the 2005 and 2006 seasons.



848 *Figure 3. Comparison of the Christiansen uniformity coefficient (CUC) of the average*
849 *irrigation depth (ID_C) collected into the pluviometers above maize and alfalfa for the*
850 *2005 and 2006 seasons.*

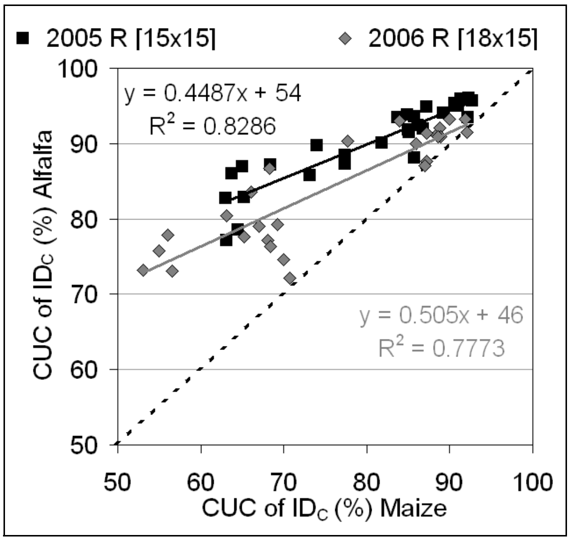


Figure 4. Comparison of the Wind Drift and Evaporation Losses (WDEL) between alfalfa and maize for the 2005 and 2006 seasons.

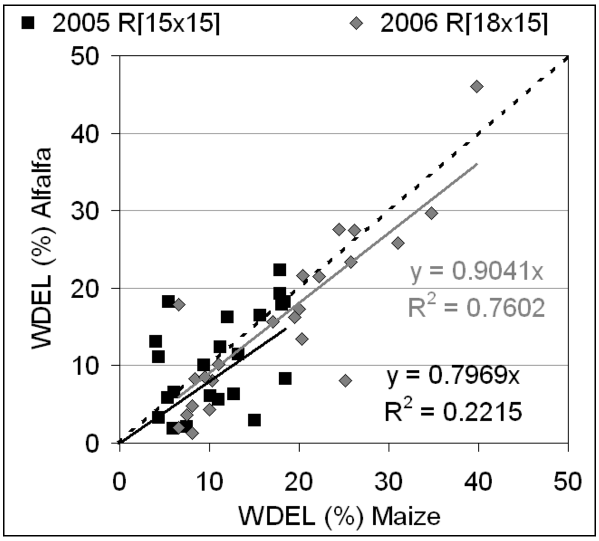


Figure 5. Comparison of the soil water recharge 24 h after irrigation (RW) in the 0-80 cm soil profile between alfalfa and maize in the crop lines (RW_{CL}) and between the crop lines (RW_{BCL}) positions for the 2005 season.

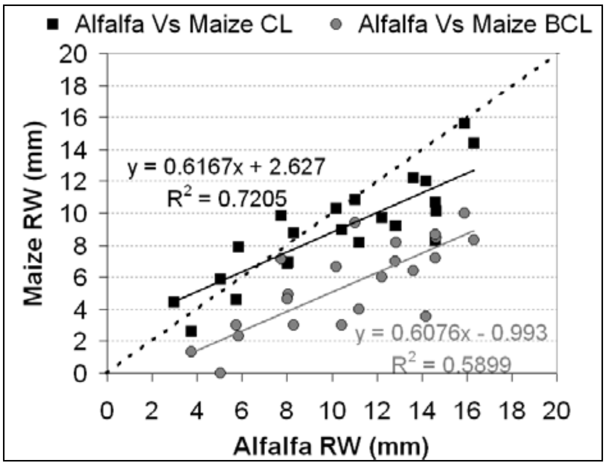


Figure 6. Christiansen uniformity coefficients (CUC) of the water depth collected above the crops after irrigation (ID_C), and of the soil water recharge (RW) 24 h after irrigation within the 0-80 cm soil profile in the crop lines (CL) and between the crop lines (BCL) for maize (a) and for alfalfa (b).

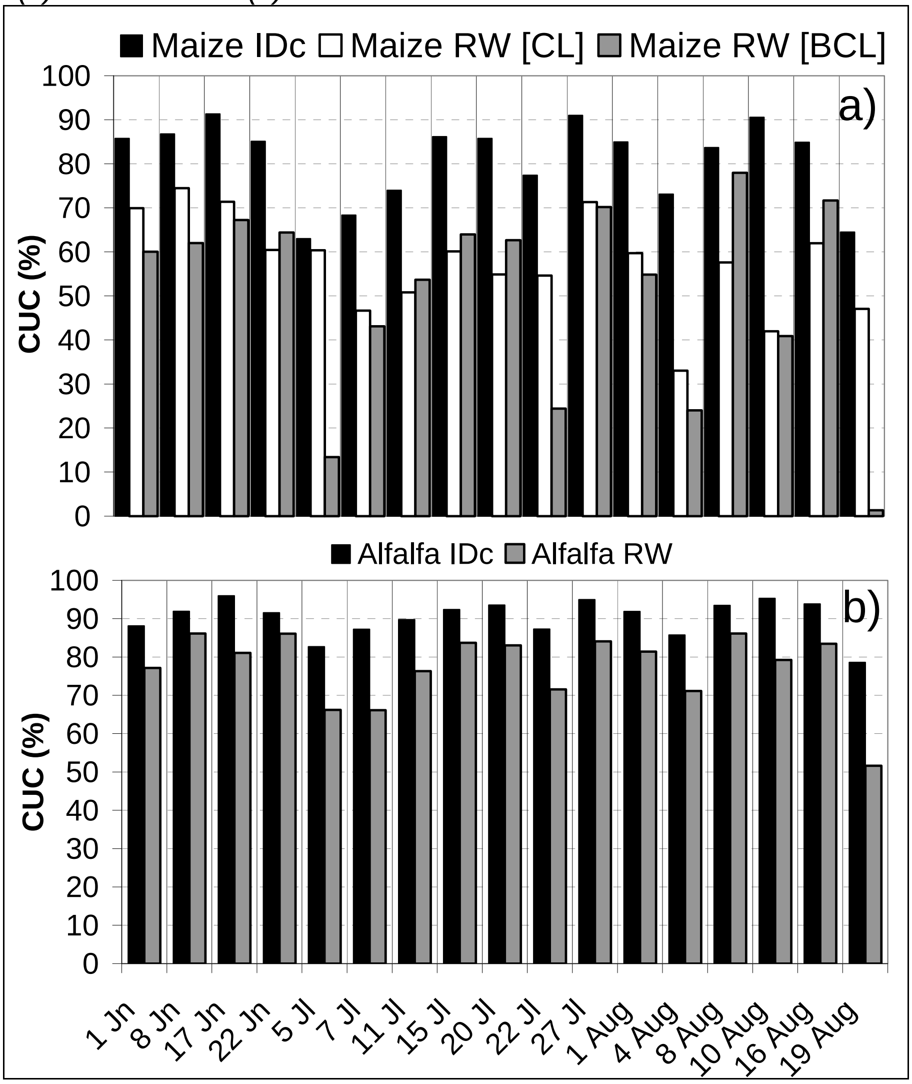
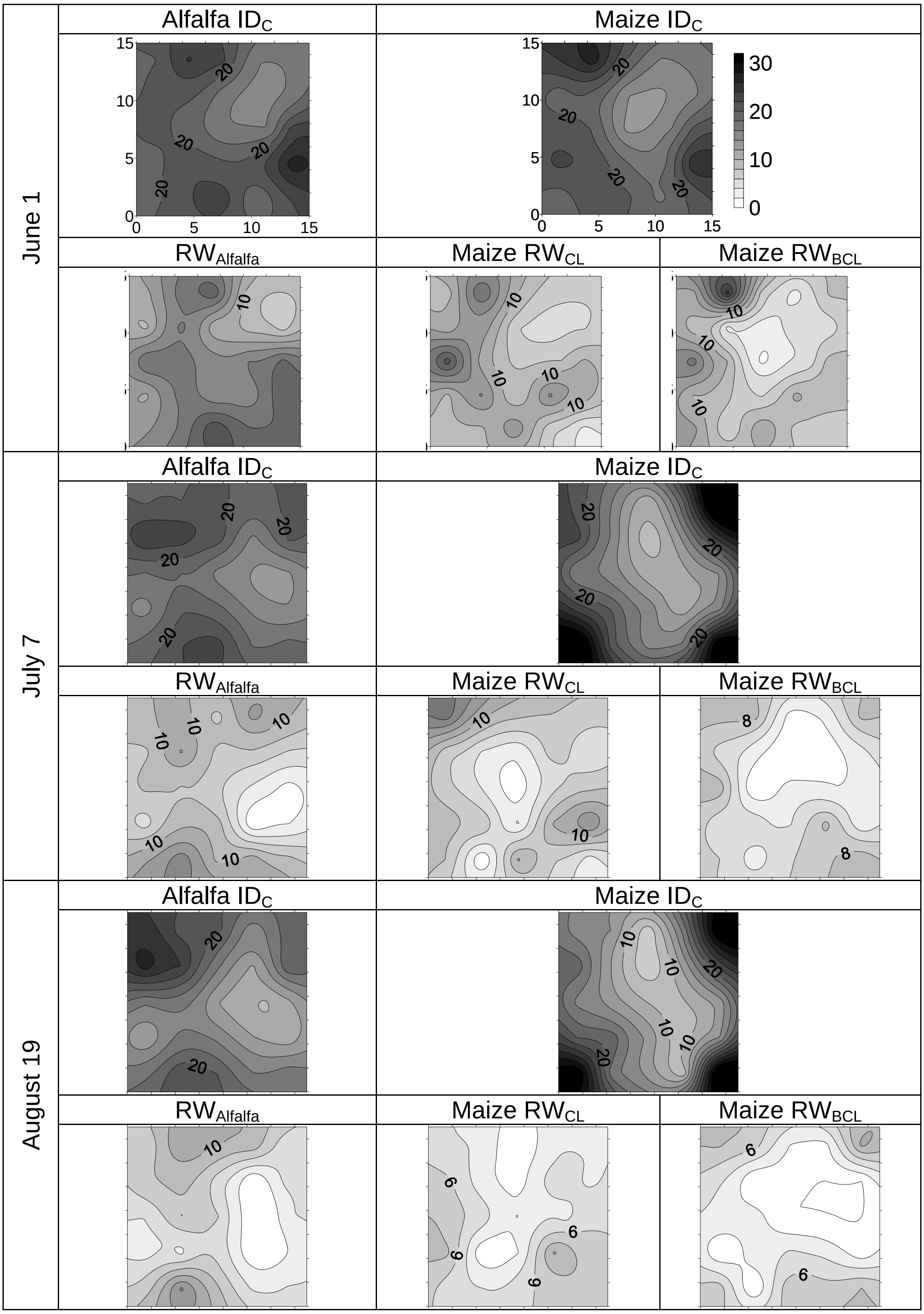


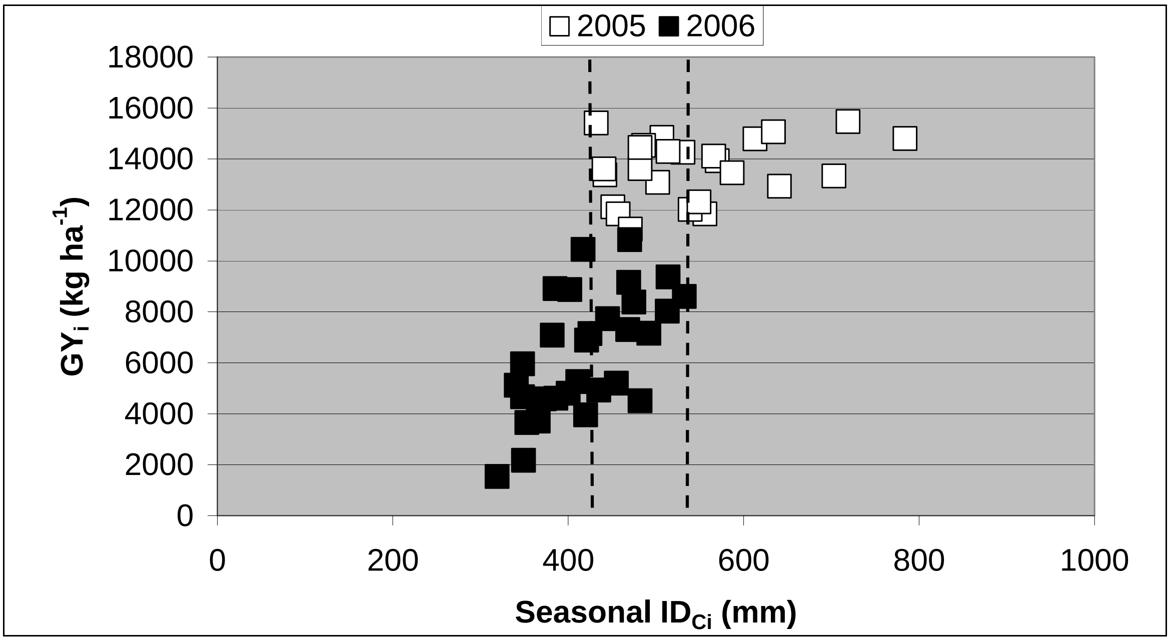
Figure 7. Distribution of the irrigation water depth above the crops (ID_C) and of the soil water recharge (RW) 24 h after the irrigation within the 0-80 cm soil profile for three irrigation events performed in 2005. RW for maize is presented for the crop lines (RW_{CL}) and between the crop lines (RW_{BCL}) positions.



864 *Figure 8. Variation of the maize grain yield (GY_i) with the irrigation depth (ID_{Ci})*

865 *accumulated during the 2005 and 2006 seasons. Each point represents a parcel within*

866 *the experimental area.*



867